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COHERENT BEAM COMBINING OF FIBER AMPLIFIERS IN A kW REGIME

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Interim Report

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Reported are kW level results for coherent beam combining experiments of high power fiber amplifiers performed in the High Power Fiber Laser Test Bed, AFRL/RDLA.

14. ABSTRACT: We report kW scale coherent beam combination (CBC) of both conventional silica fiber and photonic crystal fiber (PCF) amplifiers via LOCSET phase locking technology. Single-frequency CBC of 16 100W fiber lasers with 1.4 kW total output power is presented. In addition, kW scale CBC of novel SBS suppressive PCF amplifiers is presented. Three 350W PCF amplifiers arranged in a filled aperture configuration were combined into a single kW level laser beam. Notably, the experiments produced residual phase errors of $\lambda/25$, and $\lambda/18$, respectively.

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Coherent Beam Combining of Fiber Amplifiers in a kW Regime

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Abstract: We report kW scale coherent beam combination (CBC) of both conventional silica fiber and photonic crystal fiber (PCF) amplifiers via LOCSET phase locking technology. Single-frequency CBC of 16 100W fiber lasers with 1.4 kW total output power is presented. In addition, kW scale CBC of novel SBS suppressive PCF amplifiers is presented. Three 350W PCF amplifiers arranged in a filled aperture configuration were combined into a single kW level laser beam. Notably, the experiments produced residual phase errors of λ/25, and λ /18, respectively.

OCIS codes: (060.2320) Fiber optic amplifiers & oscillators; (140.3290) Lasers arrays; (140.3298) Laser beam combining.

1. Introduction

Fiber laser systems with a broad range of industrial [1], medical [2], and directed energy (DE) applications [3], have evolved rapidly over the past decade. Fiber lasers offer several advantages over conventional solid-state and chemical lasers; including compactness, near diffraction-limited beam quality, superior thermal-optical properties, and high output efficiencies. Despite their advantages, the powers currently available from single-mode fibers are limited by surface damage, thermal loads and nonlinear optical effects. Single-mode fiber lasers are expected to soon reach their physical limits where maximum broadband powers of ~10-15 kW and narrow linewidth (single-frequency) powers of 2 kW are predicted [4]. As a result, beam combination techniques where multiple low power lasers are efficiently combined into a single high-power output beam are being actively researched.

The major beam combining techniques developed can be broadly categorized into coherent [5] or incoherent (spectral) [6] beam combining approaches. In spectral beam combining (SBC), incoherent beams of different wavelengths are superimposed creating a singular beam of multiple colors. SBC has the advantage of not requiring active phase control or mutual temporal coherence of the individual beams. Although combined powers of 2 kW (with four elements) have been reported [6], SBC channel scalability may be limited by the finite fiber gain bandwidth (Ytterbium bandwidth ~ 50 nm) and broad output bandwidth.

In terms of DE applications where maximum brightness and power on target is desired, CBC is appealing. Here, assuming equal subaperture beam diameters, the on-axis far-field irradiance is N^2 times the irradiance of a single laser beam and N times the irradiance of an incoherently combined laser [7]. CBC can be further divided into techniques that use active [5], or passive techniques [8], to force coherence between array elements. Active CBC uses electronic feedback to control the phases of the laser array elements, while passive CBC relies on self-phase locking via passive coupling mechanisms (i.e., fiber ring oscillator, Self-Fourier cavity) to coherently combine lasers. Although channel scalability appears limited for passive CBC [9], active CBC with channel scalability of 48 elements has been reported [10] and channel counts of up to 100~200 appear feasible.

To date combined powers of 0.7 kW (4 elements) [7] and 1.2 kW (3 elements) [11] have been reported for single-frequency and broadband CBC, respectively. Towards that end, we report successful beam combination of sixteen narrow linewidth 100 W lasers into a single kilowatt class (1.4 kW) laser beam. The lasers beams were arranged in a 2-dimensional 4 x 4 tiled laser array and were coherently combined via Locking of Optical Coherence by Single-detector Electronic-frequency Tagging (LOCSET). Moreover, kW scale CBC of three 350 W PCF amplifiers in a filled aperture configuration is reported. Using electronic feedback to control the phases of the individual lasers, we the measured residual phase error was λ/25 for both CBC experiments. Significantly, the results represent the highest output power attained for a (single-frequency) coherently combined array of fiber lasers.

2. LOCSET

At the Air Force Research Laboratory (AFRL), a novel approach to electronic phase locking that eliminates the need for a reference beam and requires a single detector for phase correction has been developed [5] (in contrast to N detectors needed for other active CBC approaches). Notably, LOCSET is readily scalable to more than 100 elements as the residual phase error is independent of the number of array elements.

LOCSET employs a master oscillator power amplifier (MOPA) configuration where a narrow linewidth laser seeds an array of fiber amplifiers. In LOCSET each beam of the optical array is phase modulated at a unique radio frequency (RF). A portion of each beam is then sampled and directed onto a single far-field photodetector. This interference signal is then processed by the feedback electronics where the relative phase error of each element with respect to all other array elements are electronically isolated or demodulated. Consequently, demodulating the signal at the specific channel frequency, v_i, results in the following time integrated phase error signal

$$S_{Si} = R_{PD}\sqrt{P_i}\, J_1(\beta_i)\left[\sum_{j=1}^{N} J_0(\beta_j)\sqrt{P_j}\,\sin(\varphi_j - \varphi_i)\right], \qquad (1)$$

where R_{PD} is the detector responsivity, β_i and β_j are the RF phase modulation amplitudes in the i^{th} and j^{th} array elements, P_i and P_j are the optical powers incident on the photodetector, and J_0 and J_1 are Bessel functions of the first kind for the zero and first order, respectively. As expected, the phase error signal is proportional to the sine of the phase difference between the i^{th} and j^{th} elements. Subsequently, each demodulated output is sent to phase adjusters ($LiNbO_3$ electro-optic phase modulators) in a control feedback loop applying appropriate phase corrections to each amplifier chain and coherently combining the N discrete fiber lasers. Using LOCSET coherent combination of sixteen fiber lasers at low power (~mW level) with record phase stability of λ/60 has been demonstrated [12]

3. High Power kW Scale Coherent Beam Combining of Fiber Lasers

Coherent beam combination of fiber lasers via LOCSET was extended into the kilowatt regime. A low-power Non-Planar Ring Oscillator (NPRO) laser was used to seed sixteen fiber laser amplifiers. Specifically, each amplifier chain consisted of three fiber amplifier stages that produced 100 W of near diffraction-limited (M^2~1.1-1.2) output power. Moreover, to overcome nonlinear Stimulated Brillouin Scattering (SBS) effects a two-stage thermal gradient was applied to the power amplifier. The sixteen output laser beams were then collimated (3-mm beam diameter) and directed to an external high-power isolator for optical return protection. However, due to the thermal lensing and astigmatic aberrations introduced by the isolators (at high powers), the near diffraction-limited output beams from each fiber laser were impaired (M^2~1.3-1.5).

A schematic of the MOPA arrangement for the kW scale beam combination is shown in Fig. 1a. The sixteen lasers were arranged in a tiled 4 x 4 laser array where each beam was directed onto a far-field focusing lens by turning prisms. Subsequently, the sixteen beams were combined in the far-field where LOCSET was used to coherently combine the lasers. A total output power of 1.4 kW was achieved with a residual phase fluctuation of λ/25. The total power measured includes losses introduced by the system collimating and beam directing optics. In addition, the resulting phase locked beam profiles for the locked and unlocked beams are shown in Fig. 1b and Fig. 1c, respectively. Unfortunately, due to the size of the prisms (12.5 mm) a low tiled array fill factor was attained (7% fill factor). The ensuing low array fill factor results in substantial power in the side lobes. Nevertheless, the phase locked beam profile exhibits a stable interference fringe pattern with amplified intensity. Thereby, confirming single-frequency kilowatt scale CBC of sixteen fiber lasers.

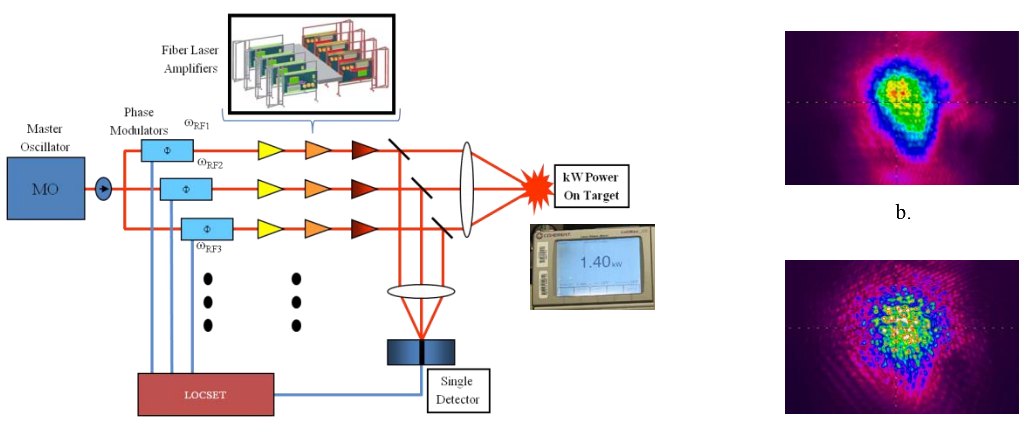
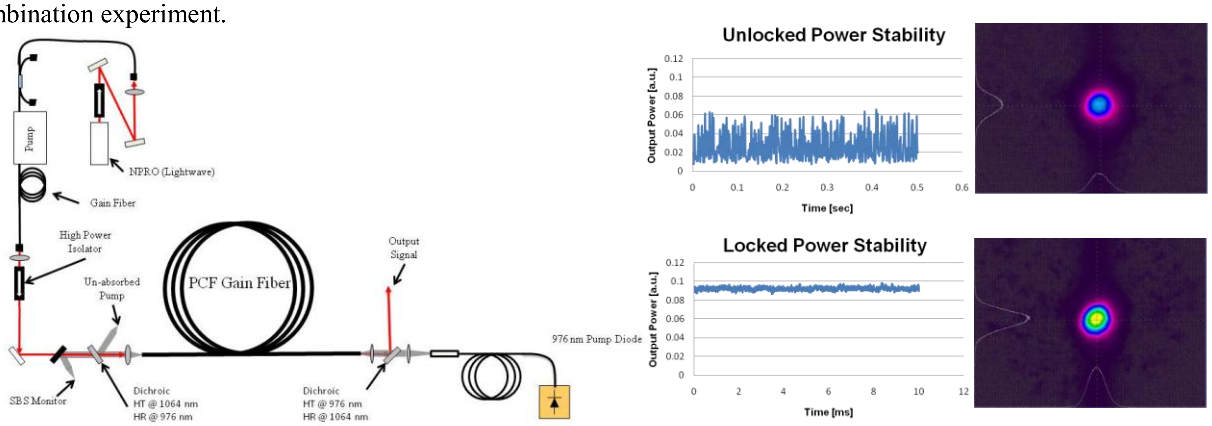


Fig. 2. a. LOCSET kW beam combining MOPA schematic. b. 16 element combined unlocked beam profile. c. 16 element combined phase locked beam profile.

Kilowatt scale beam combining was also attained with PCF amplifiers, which are an attractive means to mitigate nonlinear effects in single-frequency fiber lasers. With PCFs, micron-sized air holes in the cladding allow for precise control of the effective index leading to larger core diameters while maintaining single-mode operation. Recently, we developed a novel SBS suppressive PCF amplifier with an output power of 400 W and good beam quality (M^2~1.2-1.3) [13]. The PCF design is based on a segmented acoustic core (SAC) fiber that is doped such that

the core segments are optically uniform but acoustically inhomogeneous. The acoustically modified PCF (Yb doped DC-35-400 fiber) results in multiple Brillouin Gain Spectrum (BGS) peaks that help suppress SBS in single-frequency fiber lasers [13].

An experimental setup of the PCF amplifier with a counter-propagating pump scheme is presented in Fig. 2a. Similarly, three 350 W SAC fiber laser amplifiers were built and arranged in a filled aperture configuration. The beams were coherently combined through beam splitters and LOCSET phase locking electronics, with the resulting output beam profiles shown in Fig. 2b. The beam combination experiments resulted in 1.04 kW of combined power with a residual phase fluctuation of λ/18. More importantly, the filled aperture arrangement results in 1 kW of power in a single central lobe (no sidelobes). Thus, single frequency kW coherent beam combination has been demonstrated with both conventional silica and novel SBS suppressive PCF fiber lasers. We note that LOCSET beam combining can be extended to broader linewidths, assuming appropriate path length matching is performed. Nevertheless, the reported results represent the highest output power ever recorded for a coherent fiber laser beam combination experiment.



a. b.

Fig. 2. a. 350 W PCF amplifier experimental setup with counter-propagating pump scheme. b. Coherently combined unlocked and locked output beam profiles.

LOCSET is a well established scheme that has been successfully employed by companies such as Northrop Grumman, Lockheed Martin, and Raytheon for beam combination. Notably, the recent high power experiments establish LOCSETs viability at kilowatt power levels. Moreover, due to LOCSETs high operational bandwidth (65 kHz), low phase error, and narrow linewidth of the lasers, LOCSET appears readily scalable for efficient combination of over 100 lasers.

4. References

[1] L. Quintino, A. Costa, R. Miranda, D. Yapp, V. Kumar, and C. J. Kong, "Welding with high power fiber lasers- A preliminary study," Materials & Design **28**, 1231-1237 (2007).

[2] S. D. Jackson and A. Lauto, "Diode-pumped fiber lasers: A new clinical tool?," Lasers in Surgery and Medicine **30**, 184-190 (2002).

[3] P. Sprangle, J. Peñano, B. Hafizi, and A. Ting, " Incoherent Combining of high-Power Fiber Lasers for Long-Range Directed Applications," Journal of Directed Energy **2**, 273-284 (2007).

[4] J. W. Dawson, M. J. Messerly, R. J. Beach, M. Y. Shverdin, E. A. Stappaerts, A. K. Sridharan, P. H. Pax, J. E. Heebner, C. W. Siders, and C. P. J. Barty, "Analysis of the scalability of diffraction-limited fiber lasers and amplifiers to high average power," Optics Express **16**, 13240-13266 (2008).

[5] T. M. Shay, "Theory of electronically phased coherent beam combination without a reference beam," Optics Express **14**, 12188-12195 (2006).

[6] C. Wirth, O. Schmidt, I. Tsybin, T. Schreiber, T. Peschel, F. Bruckner, T. Clausnitzer, J. Limpert, R. Eberhardt, A. Tunnermann, M. Gowin, E. ten Have, K. Ludewigt, and M. Jung, "2 kW incoherent beam combining of four narrow-linewidth photonic crystal fiber amplifiers," Optics Express **17**, 1178-1183 (2009).

[7] M. A. Vorontsov and S. L. Lachinova, "Laser Beam Projection with Adaptive Array of Fiber Collimators. I. Basic Considerations for Analysis," Journal of Optical Society of America A 25, 1949-1959 (2008).

[8] T. H. Loftus, A. M. Thomas, M. Norsen, J. Minelly, P. Jones, E. Honea, S. A. Shakir, S. Hendow, W. Culver, B. Nelson, and M. Fitelson, "Four-Channel, High Power Passively Phase Locked Fiber Array," *Advanced Solid-State Photonics* 2008, WA4 (2008).

[9] J. Rothenberg, "Passive coherent phasing of fiber laser arrays," Proceedings of SPIE 6873, 687315-687315-9 (2008).

[10] C. X. Yu, J. E. Kansky, S.E.J. Shaw, D. V. Murphy, and C. Higgs, "Coherent beam combining of large number of PM fibers in 2-D fiber array," Electronic Letters **42**, 1024-1025 (2006).

[11] C. X. Yu, S. J. Augst, S. Redmond, D. V. Murphy, A. Sanchez, and T. Y. Fan. "Phase Coherence, Phase Noise and Phase Control in High-Power Yb Fiber Amplifiers, *23rd Annual Solid-State and Diode Laser Technology Review* (SSDLTR 2010).

[12] T. M. Shay, J. T. Baker, A. D. Sanchez, C. A. Robin, C. L. Vergien, A. Flores, C. Zeringue, D. Gallant, C. A. Lu, B. Pulford, T. J. Bronder, and A. Lucero, "Phasing of High Power Fiber Amplifier Arrays*," 2010 Advanced Solid-State Photonics (ASSP)*, AMA1 (2010).

[13] C. Robin, I. Dajani, C. Vergien, C. Zeringue, and T. M. Shay, "Experimental and theoretical studies of single frequency fiber amplifier with output of 400 W," Proceedings of SPIE Vol. **7580**, 75801I-1-75801I-1-11 (2010).

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